HPC LESSONS FROM 30 YEARS OF PRACTICE IN CFD TOWARDS AIRCRAFT DESIGN AND ANALYSIS

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8TH ANNUAL CHAPEL IMPLEMENTERS AND USERS WORKSHOP, ONLINE, 2021

POLYTECHNIQUE MONTRÉAL

ACKNOWLEDGEMENTS

- Bombardier Aerospace
- CRAY/HPE
- CAE Inc.

- NSERC-CRSNG
- CRIAQ

- Compute Canada
- Calcul Québec

- Polytechnique Montréal, especially students/researcher
- Internet, a few illustrations
- CHIUW 2021 organizing committee

OUTLINE

- Crash course in Aircraft design (short of being Rocket Scientist)
- Crash course in Aerodynamic Analysis and Design
- Computational Fluid Dynamics (CFD)
- HPC
  - Case studies
  - Chapel breakthrough
- Conclusion
- Vision

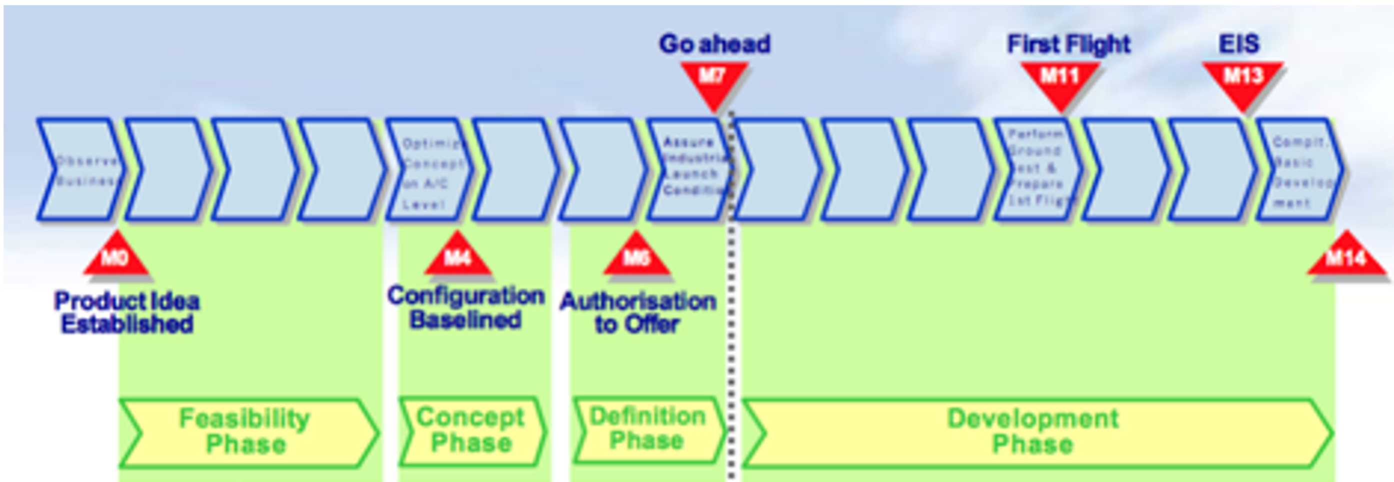
What's special about Montreal?

- 3rd largest aerospace cluster, behind Toulouse (Airbus), Seattle (Boeing)
- Only region where, should you isolate it, an entire aircraft can be designed, built, flight tested and manufactured!
- Hosts the International Civil Aviation Organization (ICAO), United Nations and International Air Transport Association (IATA): international consensus on solutions towards global warming, secure flights and planet-friendly travel (i.e. recycling).

- Notables:
- Industries: Bombardier, Pratt&Whitney Canada, Bell Helicopter (Civil), CAE (flight simulators), 2nd and 3rd tier: Landing gear, flight controls, etc.
- Best Student Universities: no. 1 city in North-America (182 000 students), ahead of no. 2 Boston (150 000). Worldwide ranks no. 6. (QS ranking, 2019)
- World-class AI hub, lead by prof. Yoshua Bengio (Turing award, 2018 with Geoffrey Hinton, and Yann LeCun)

AIRCRAFT DESIGN THEORY -> 4 PHASES (EASY!!!)

Source: Flaig, Axel, Airbus A380: Solutions to the Aerodynamic Challenges of Designing the World's Largest Passenger Aircraft, 2008



0. 1. 2. 3. 4.

Commercial service

AIRCRAFT DESIGN THEORY -> 4 PHASES (EASY!!!)

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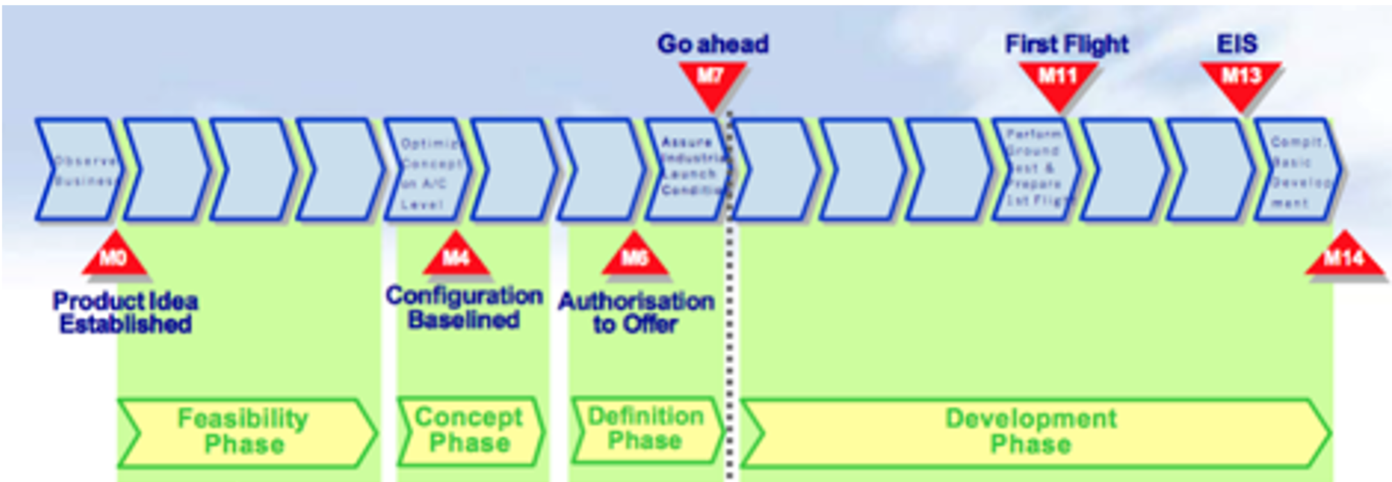
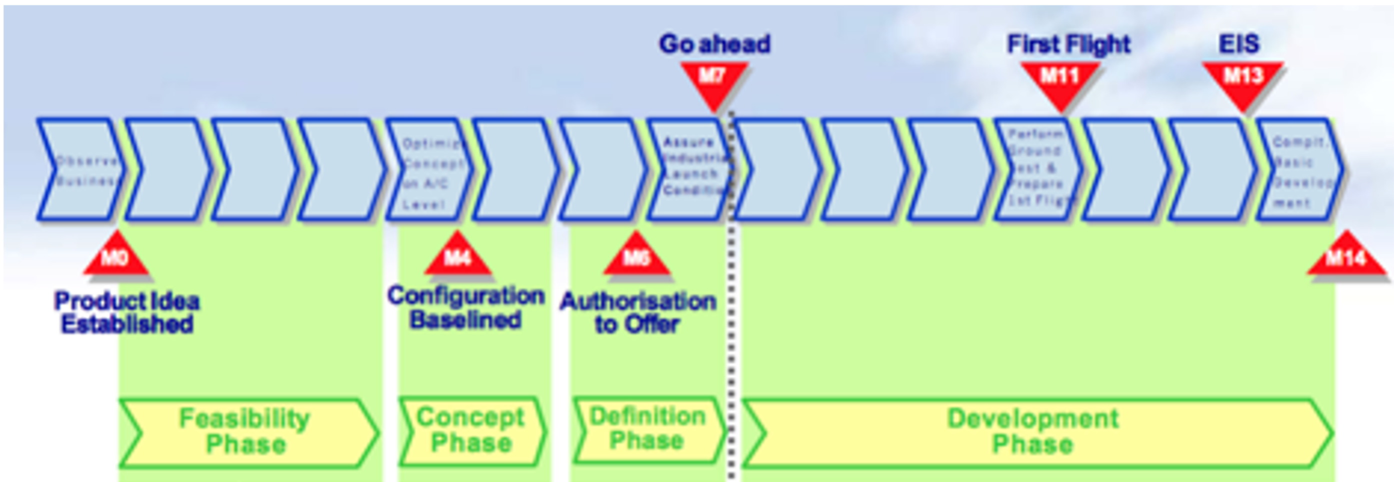


0. $ 1. $$ 2. $$$ 3. $$$$ 4.

Commercial service

AIRCRAFT DESIGN REALITY -> SEVERAL PHASES

Source: Flaig, Axel, Airbus A380: Solutions to the Aerodynamic Challenges of Designing the World's Largest Passenger Aircraft, 2008



0. $ 1. $$ 2. $$$ 3. 4.

$$$

$$$$

$$$$$

$$$$$$$$$
5-15 Billions

$$$$$$$$$$$
30 Billions

QUESTION

How to treat aerodynamics?

QUESTION

How to treat aerodynamics?

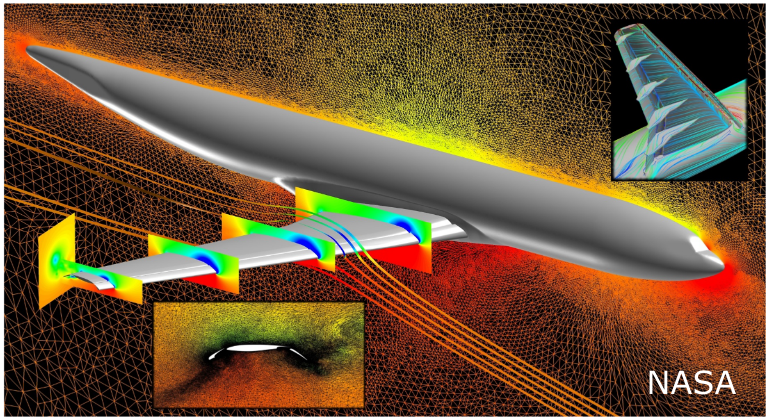
- Key performance metric (Drag)
- Key security metric (stall, buffet)
- Key aircraft program development metric
  - 1st wind-tunnel tests
  - 1st flight tests

- Historical source of major catastrophes
  - Technical, human, financial

METHODS USED FOR AERODYNAMIC ANALYSIS

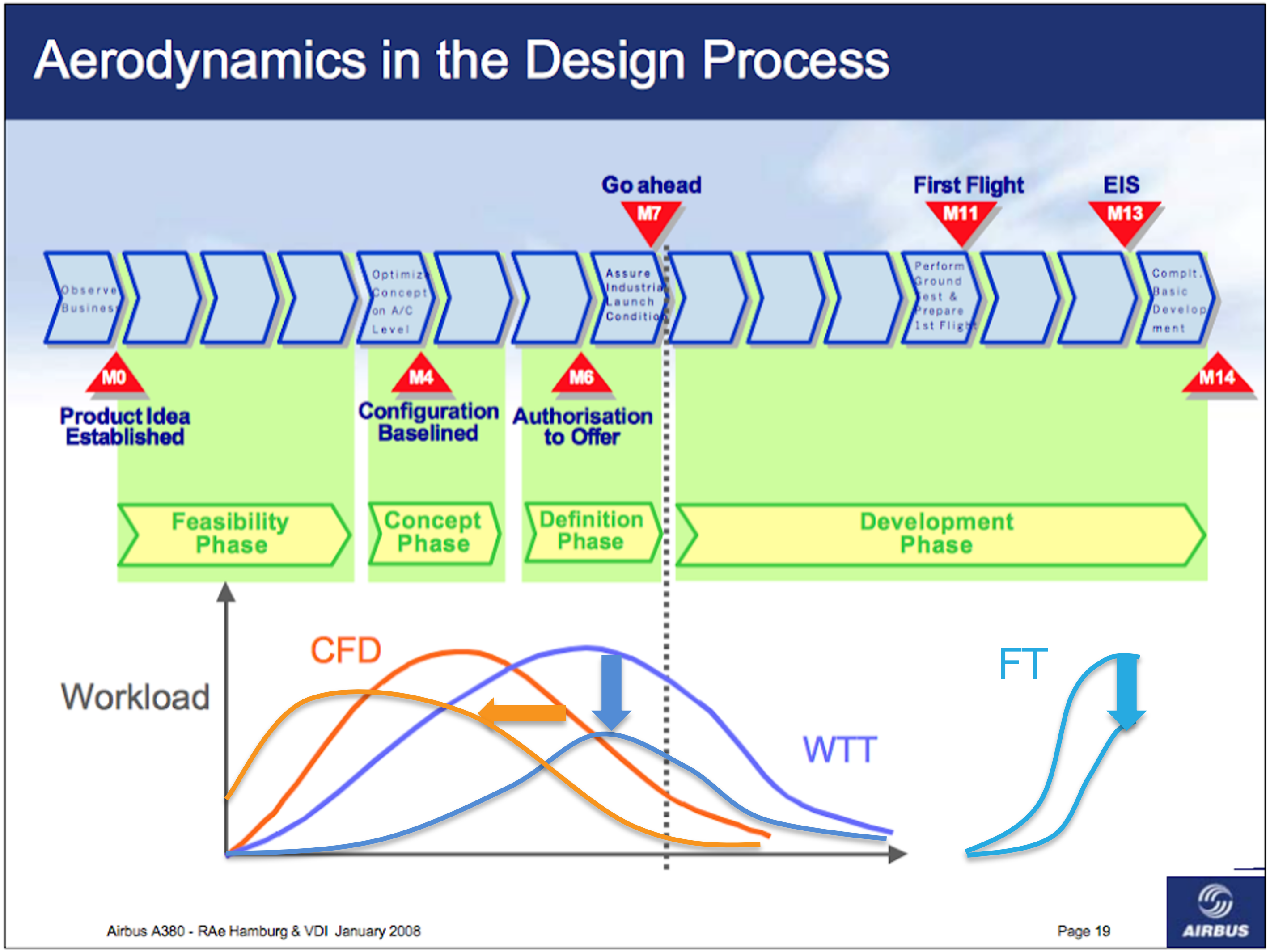
Flight tests ~100 000$/hr
Prototype: 1 Billion$

Wind-tunnel tests ~1000-10 000$/hr
Prototype: 10 Millions$



CFD ~100-1000$/hr
Prototype: 1 Million$

AIRCRAFT/AERODYNAMIC DESIGN



- Risks
- Costs

Source: Flaig, Axel, Airbus A380: Solutions to the Aerodynamic Challenges of Designing the World's Largest Passenger Aircraft, 2008

COMPUTATIONAL FLUID DYNAMICS (AERODYNAMICS)

$$\underbrace{\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u}\right)}_{\text{Acceleration}} = \underbrace{-\nabla p}_{\text{Pressure}} + \underbrace{\nu \triangle \vec{u}}_{\text{Viscosity}}$$

$$\underbrace{\nabla\cdot\vec{u} = 0}_{\text{Continuity Equation}}$$

MIT

Physics
Viscous flows,
Subsonic/Transonic/Supersonic regimes
Multi-physics: icing,
Laminar-turbulent transition

Applied mathematics
Non-Linear Partial Differential Equations
Elliptic/Parabolic/Hyperbolic
Discretization

HPC
Source code, cache, shared-distributed memory
Heterogeneous systems: CPU, GPU, mixed-precision arithmetic

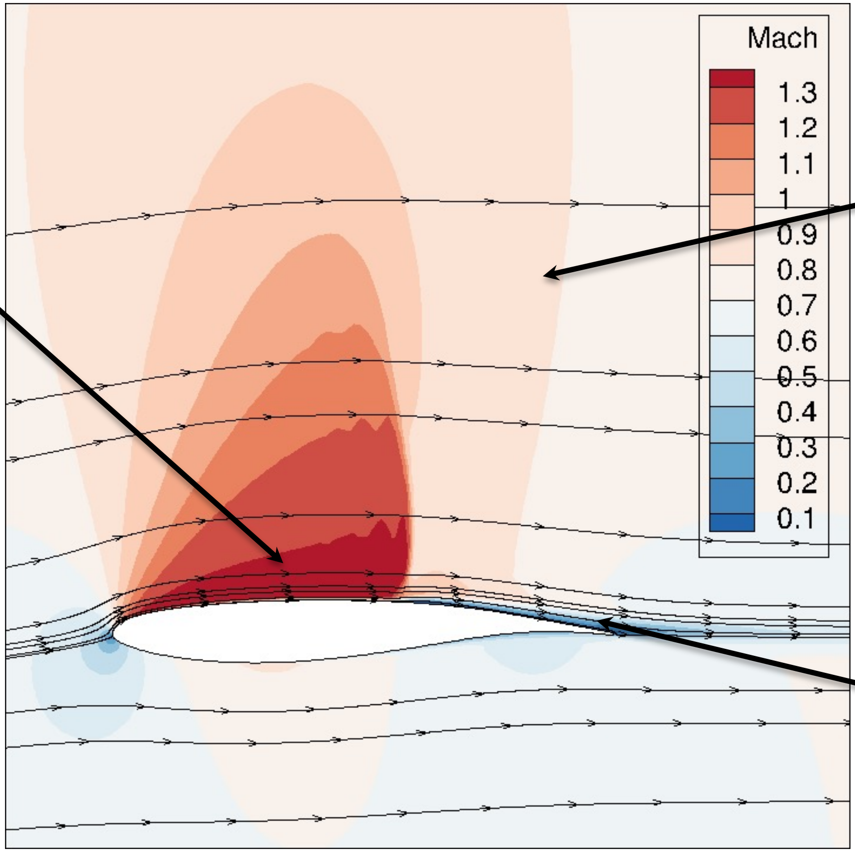
NUMERICAL METHODS: APPLICATIONS

Physics
Transonic buffet

Applied Mathematics
Elliptic, parabolic and hyperbolic flows

HPC
Source code, CPU

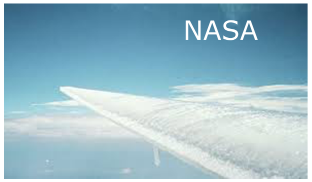
Hyperbolic
Mach > 1



Elliptic
Mach < 1

Parabolic
Viscous Boundary-Layer

CFD WORKFLOW



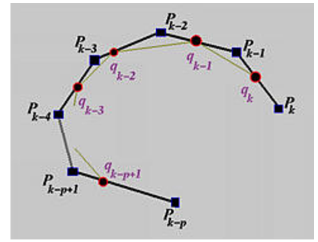
Physics

$$\underbrace{\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u}\right)}_{\text{Acceleration}} = \underbrace{-\nabla p}_{\text{Pressure}} + \underbrace{\nu \triangle \vec{u}}_{\text{Viscosity}}$$

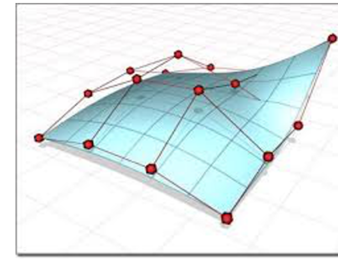
$$\underbrace{\nabla\cdot\vec{u} = 0}_{\text{Continuity Equation}}$$

MIT

Applied Math.

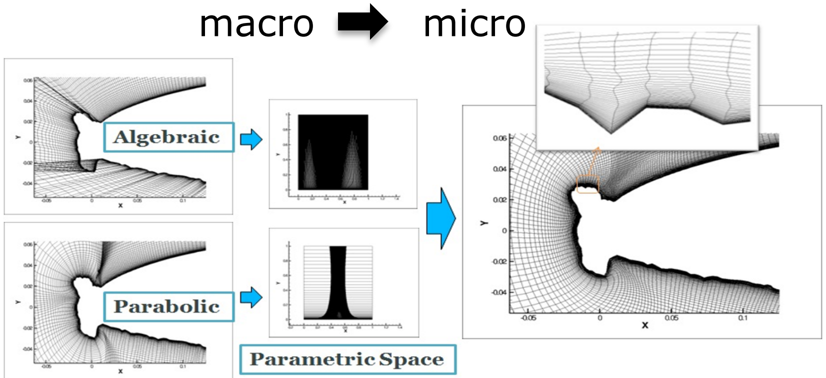


Geometry parameterization
(NURBS, CAD)

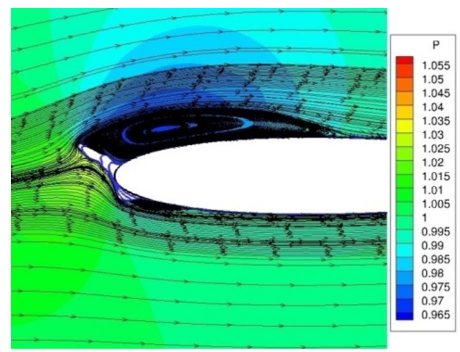


Geometry discretization
(Surface Mesh)

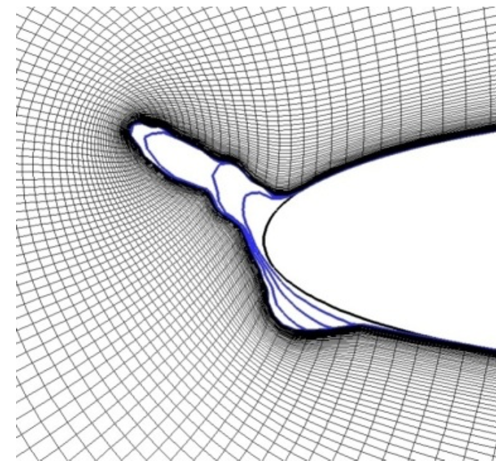
macro ➡ micro



Volumetric mesh generation
10-1000 Millions unknowns



solution:
i) flow, ii) droplets



Time-advancement
& post-processing

```
#include <stdio.h>

int main()
{
    int i;
    int a[10];
    printf("Enter student's scores: \n");
    for(i = 0; i < 10; i++) {
        scanf("%d", &a[i]);
    }
    printf("Your student's scores are: \n\n");
    for(i = 0; i < 10; i++) {
        printf("%d\n", a[i]);
    }
    return 0;
}
```

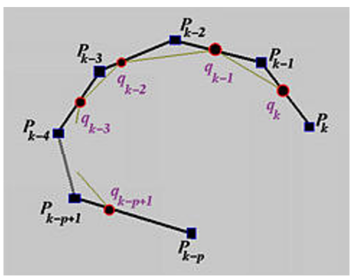
Source code

HPC

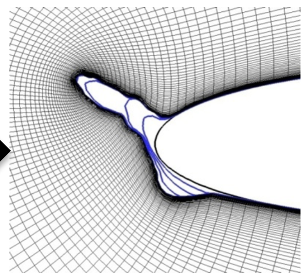
OPTIMISATION

Numerical analysis allows numerical optimisation

Analysis workflow

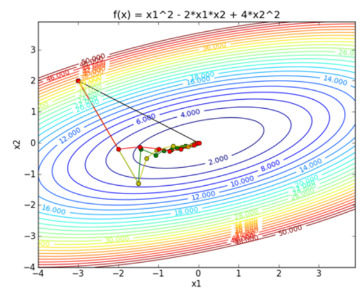


Parameterisation



Solution

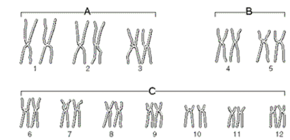
Optimisation algorithms

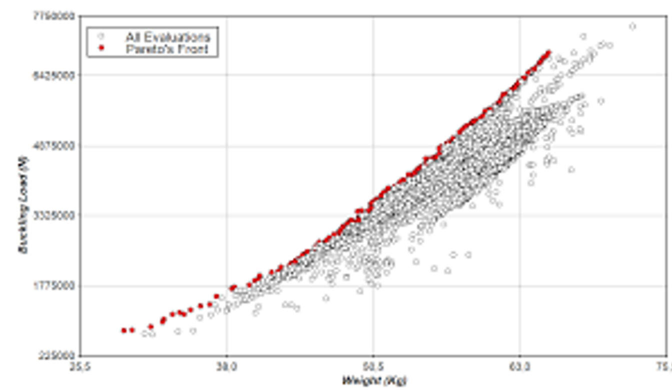


Brigham Young University

Gradient-based
(Newton)
~100 evaluations

Parameterisation





Ichrome.com

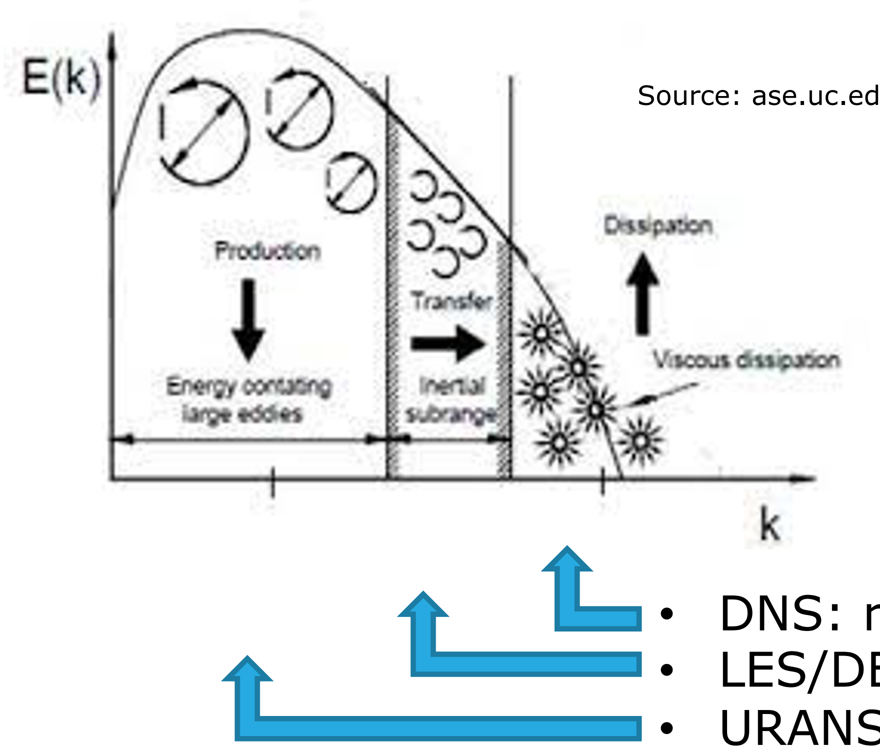
Gradient-free
(genetic)
~10^6 évaluations

Key for success

- **Model precision** (physics, numerical, geometry)
- **Computing resources and algorithm robustness**
- **Orthogonal Dimensional Space**

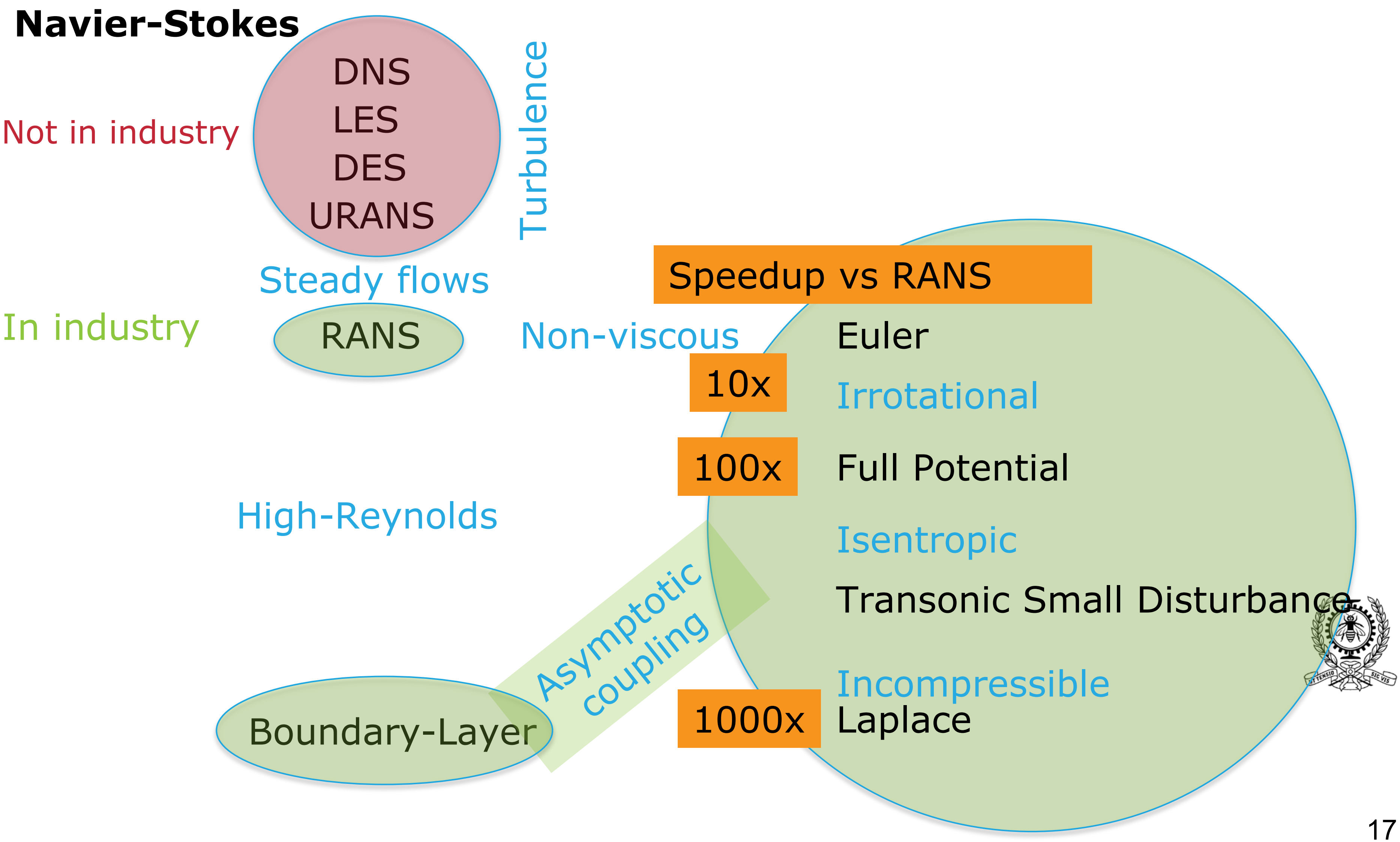
PHYSICS: TURBULENCE

- All flows can be laminar
- All laminar flows can transition to turbulence
- Turbulent flows contain eddies
- Large eddies transfer energy to smaller eddies…until the smallest eddy dissipates into heat! (Kolmogorov scale)



- DNS: resolves all scales
- LES/DES models small scales
- URANS models even more scales

SEVERAL EQUATIONS AT OUR DISPOSAL… ALL LINKED TO HPC RESOURCES



NASA CFD VISION 2030 STUDY: A PATH TO REVOLUTIONARY COMPUTATIONAL AEROSCIENCES

NASA funded a one-year **study** effort with a **world-class team** from Boeing, Pratt & Whitney, Stanford University, The Massachusetts Institute of Technology, The University of Wyoming and The **National Center for Supercomputing Applications** to develop a **long-range plan for the development of the next generation simulation-based aerospace design process.**

This report, published in March 2014, presents the findings and recommendations of this multidisciplinary team, whose goal was to formulate a knowledge-based forecast and research strategy for developing **a visionary computational fluid dynamics (CFD) capability in the notional year 2030**.

NASA CFD VISION 2030 STUDY: A PATH TO REVOLUTIONARY COMPUTATIONAL AEROSCIENCES

NASA should:

1. Develop, fund and sustain a base research and technology development program for **simulation-based analysis and design** technologies.

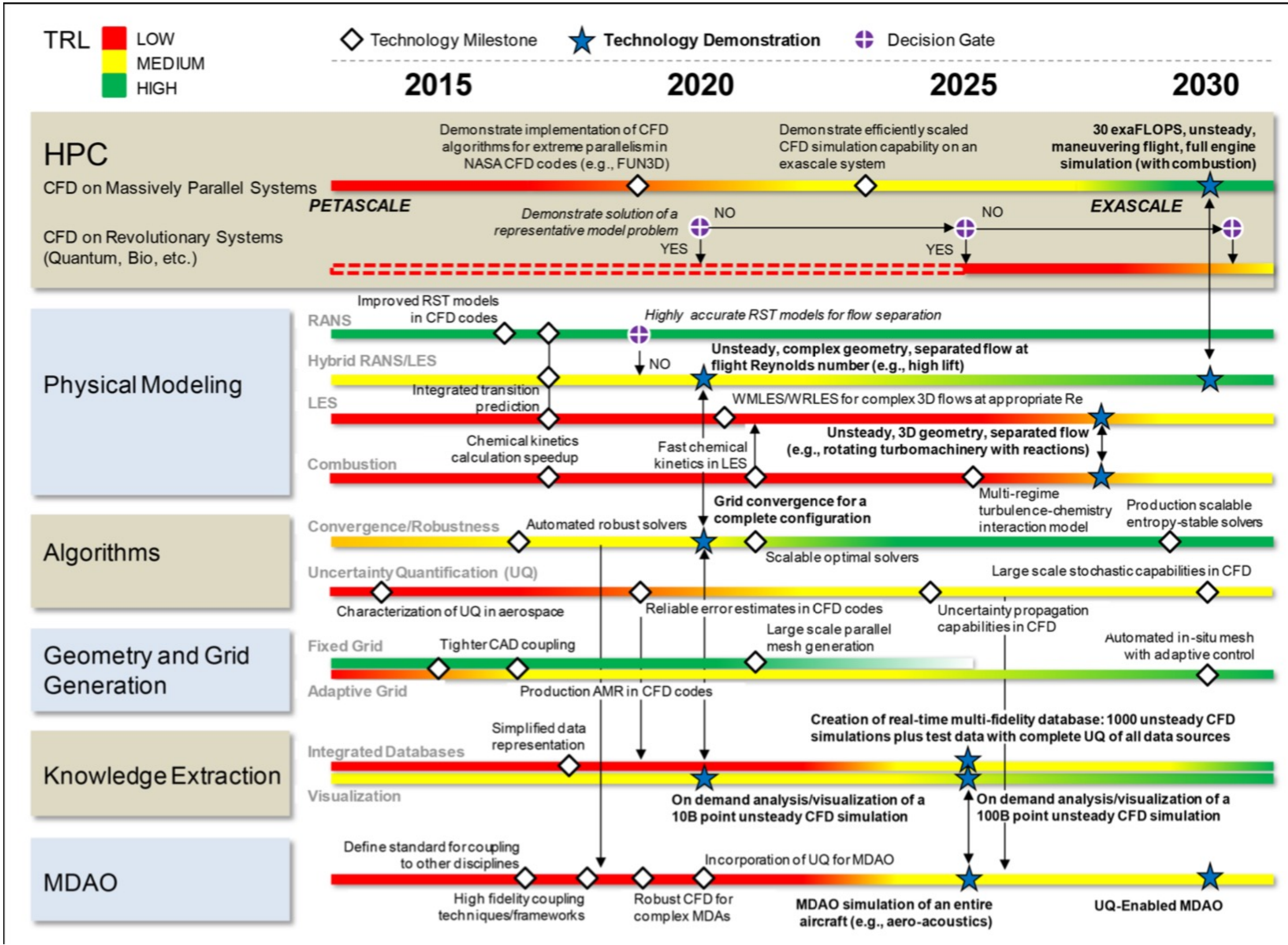
2. Develop and maintain an integrated simulation and software development infrastructure to **enable rapid CFD technology maturation**.

3. **Make available and utilize HPC systems for large-scale CFD development and testing**.

4. Lead efforts to develop and execute integrated experimental testing and **computational validation campaigns**.

5. **Develop, foster, and leverage improved collaborations with key research partners and industrial stakeholders across disciplines within the broader scientific and engineering communities**.

NASA CFD VISION 2030 STUDY: ROADMAP



AMERICAN INSTITUTE OF AERONAUTICS (AIAA)

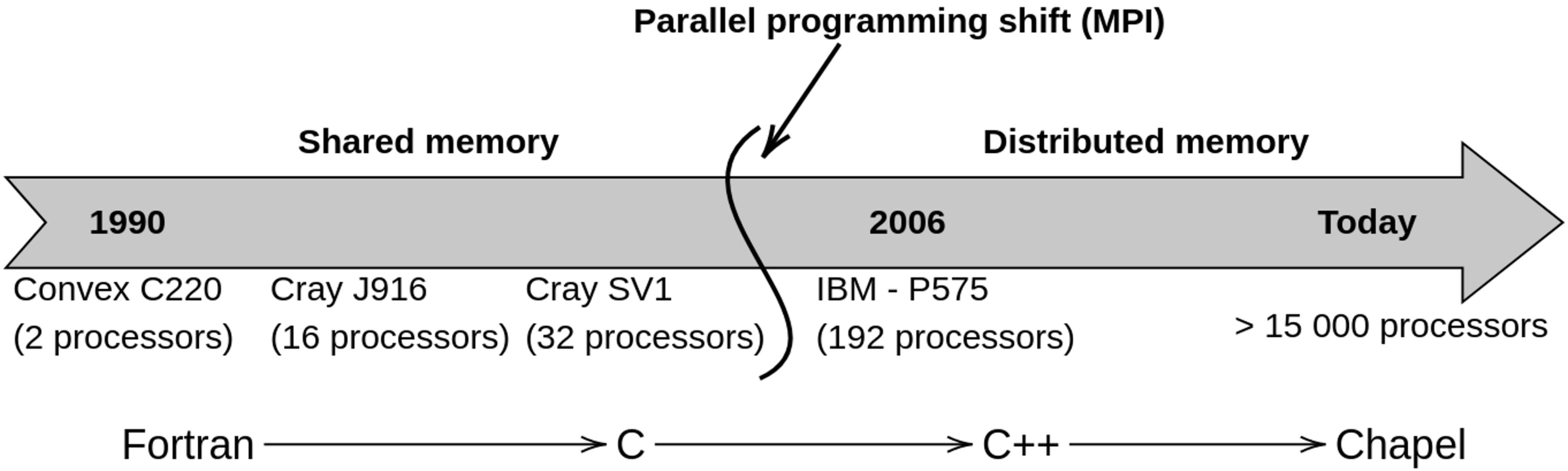
- The scientific body coordinates several **international workshops** with aim to improve modeling capabilities on HPC systems
  - Drag, Supersonic, Aeroacoustics, High-Lift, Aeroelastic, Stability and control, Geometry, Hover Prediction, High-order Schemes, etc.

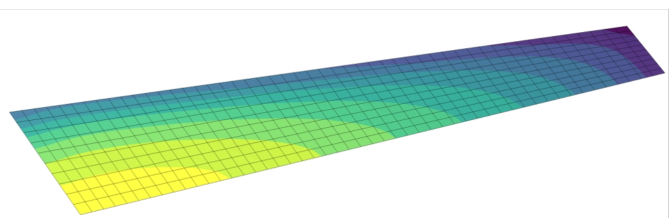
- Notable Participants
  - **Industries**: Boeing, Lockheed, GE, Textron, Bell, Bombardier (Canada), Embraer (Brazil), Dassault (France)
  - **Research Centers**: NASA, ONERA (France), NRC (Canada), JAXA (Japan)
  - **Universities**: Stanford, Oxford (UK), NTNU (Norway), Polytechique Montreal (Canada)
  - **Certification agencies**: FAA, EASA (Europe), Transport Canada

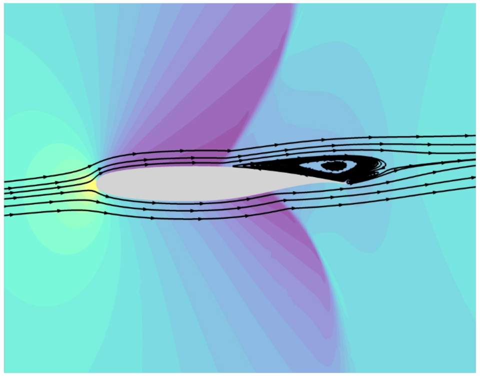
SOFTWARE AND HARDWARE

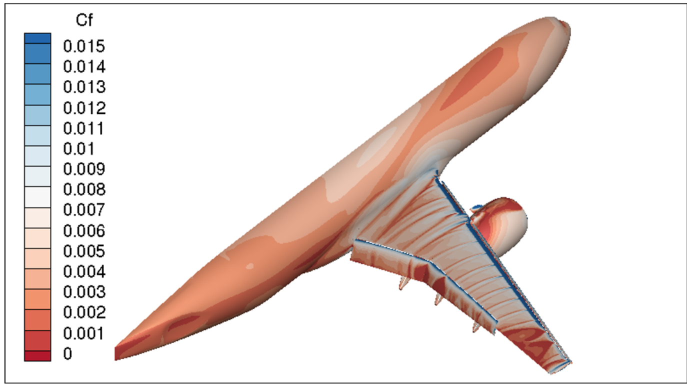
- CFD Software provides competitive advantages
  - Many developed by national research centers
    - OVERFLOW, FUN3D, CFL3D, USM3D, etc. (NASA)
    - ELSA, CEDRE (ONERA)
    - TAU, FLOWer (DLR)
  - Many are tagged with export control
  - Several are developed by industries, tagged proprietary
    - GGNS (Boeing)
    - FANSC/Dragon (Bombardier)
    - Xflow (Dassault)
  - Some developed by universities, open-source or research codes (non-commercial licence)
    - SU2 (Stanford)
    - Xflow (Michigan)
    - Diablo (UTIAS)
    - Champs (Polytechnique Montréal)

CFD HISTORY


Parallel programming shift (MPI)
Shared memory
Distributed memory
1990
2006
Today
Convex C220
(2 processors)
Cray J916
(16 processors)
Cray SV1
(32 processors)
IBM - P575
(192 processors)
> 15 000 processors
Fortran
C
C++
Chapel






Cf
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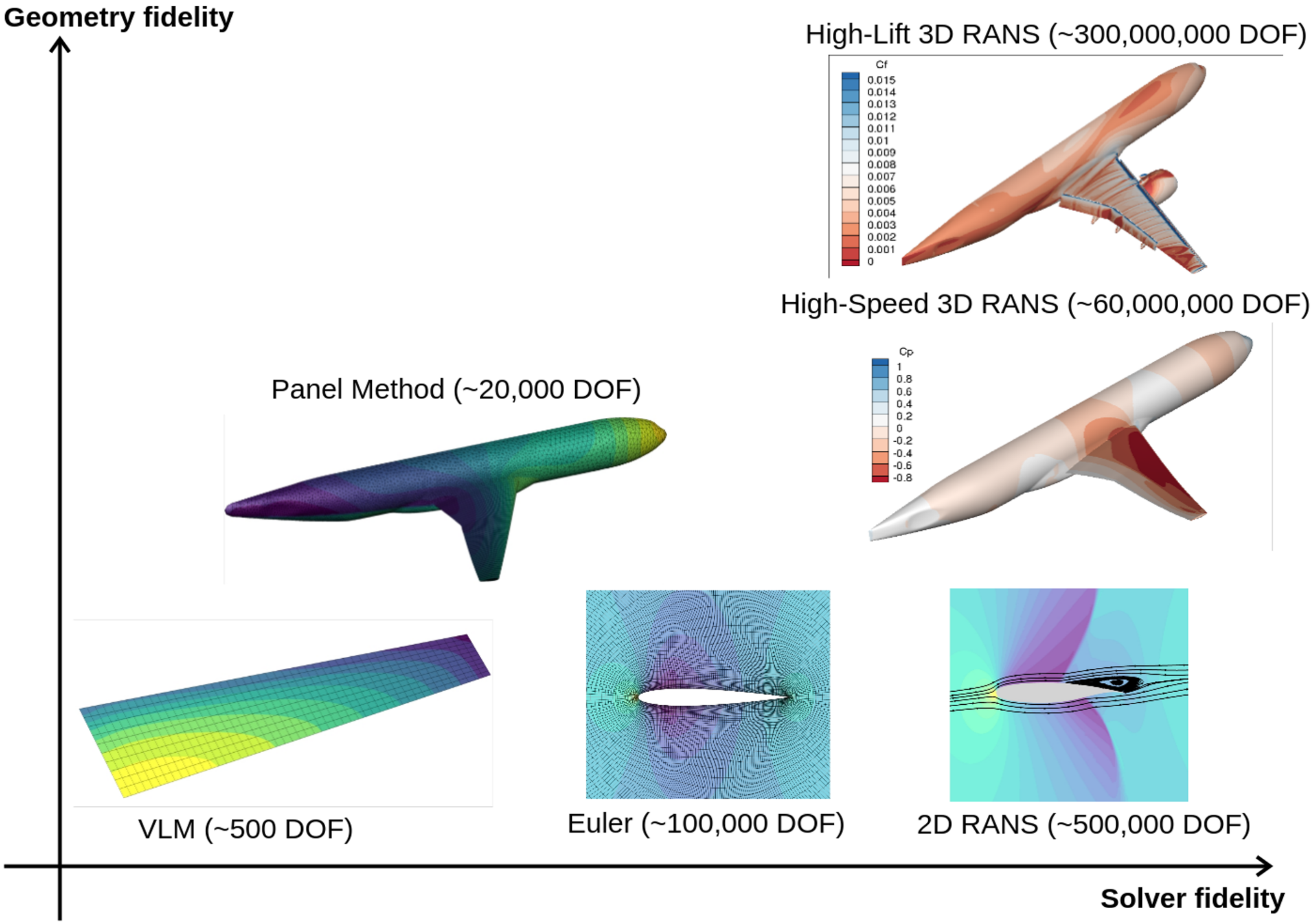
0.003
0.002
0.001
0

- Various fluid models with a large variation in problem size



LAB HISTORY AT POLYTECHNIQUE

- **NSCODE** (2012 - early 2020):
  - Shared memory 2D/2.5D structured multi-physics solver written in C/Python
  - ~800 C/header files: ~120k lines of code
  - Run by Python interface using f2py (f90 APIs)
  - Difficult to maintain at the end or even to merge new developments

- **(U)VLM** (2012 - now):
  - ~5-6 versions in different languages (Matlab, Fortran, C++, Python, Chapel)
  - The latest version in Chapel is integrated in CHAMPS

- **EULER2D** (early 2019):
  - Copy in Chapel of a small version of NSCODE as benchmark between C and Chapel that illustrated the Chapel language potential
  - ~10 Chapel files: ~1750 lines of code

- **CHAMPS** (mid 2019 - now):
  - Distributed memory 3D/2D unstructured multi-physics solver written in Chapel
  - ~120 Chapel files: ~48k lines of code

CHAMPS - CHApel Multi-Physics Simulations

- Written in Chapel:
  - Promotes programming efficiency
  - Simpler to learn for new students than C
  - Distributed memory is easier to develop for new students than with MPI
- Initially developed by 3 students until it worked enough to mention its existence
- Relies heavily on object oriented coding with generic types to promote modularity and code reuse
- Compatibility with GPU is being added: See presentation from Anthony Bouchard later today at 2:15pm PDT

- Applications:
  - Aerodynamic simulations in steady/unsteady/frequential domains and for stability analysis
  - Icing: droplet trajectory, thermodynamic models, deterministic and stochastic ice growth
  - Aeroelasticity
  - 2D mesh generation

- World-class CFD code:
  - Participation in the 1st AIAA icing workshop (2021)
  - Participation in the 4th AIAA High-lift workshop (2021)

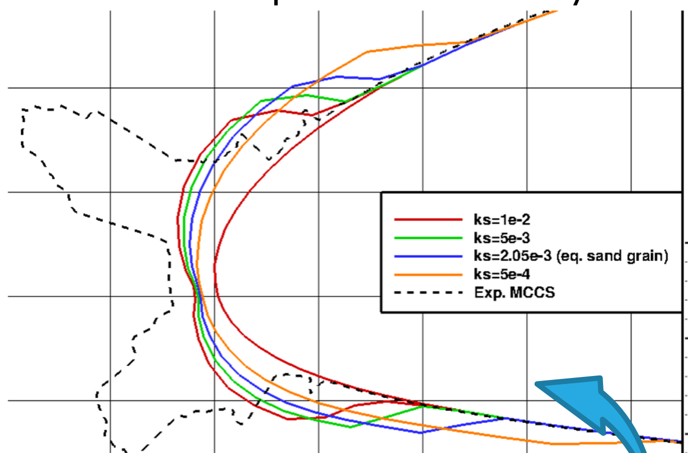
APPLICATIONS - ICING SIMULATIONS

- Icing requires multiple physical models to run in an iterative sequence at the end of which the geometry is deformed
  - A lot of potential bugs and failures!
  - Almost everything done in the lab becomes connected
  - 3D is at the edge of actual world-wide capability in icing

Experimental glaze ice on 3D swept wing

Ref: AIAA Paper 2014-2200

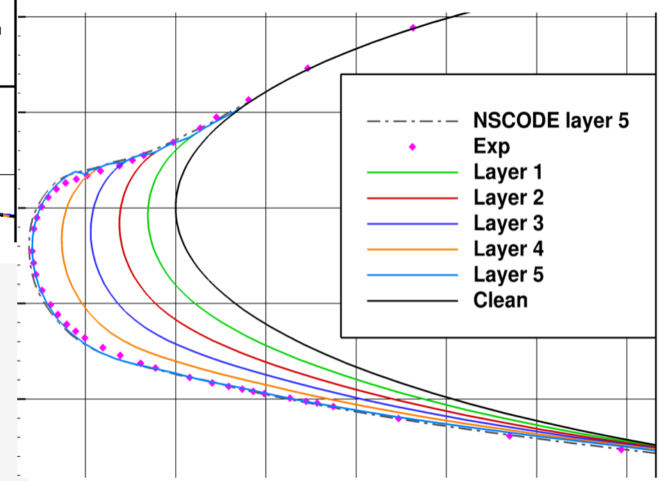
CHAMPS parametric study



Scan of experimental glaze ice on 3D extruded wing

Ref: AIAA Paper 2014-2613

2D case: CHAMPS vs NSCODE

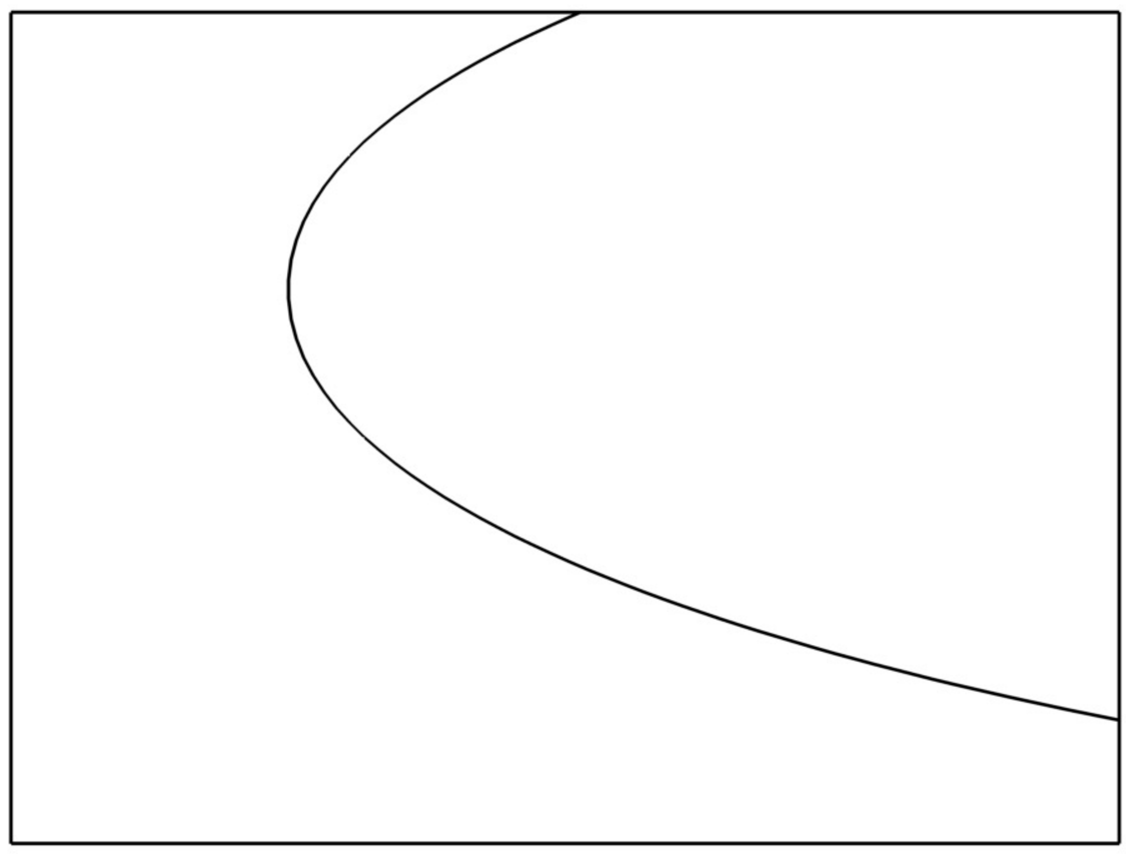


APPLICATIONS - STOCHASTIC ICING SIMULATIONS

- Droplet seeding point location and freezing depends on Pseudo-Random Numbers along physical models

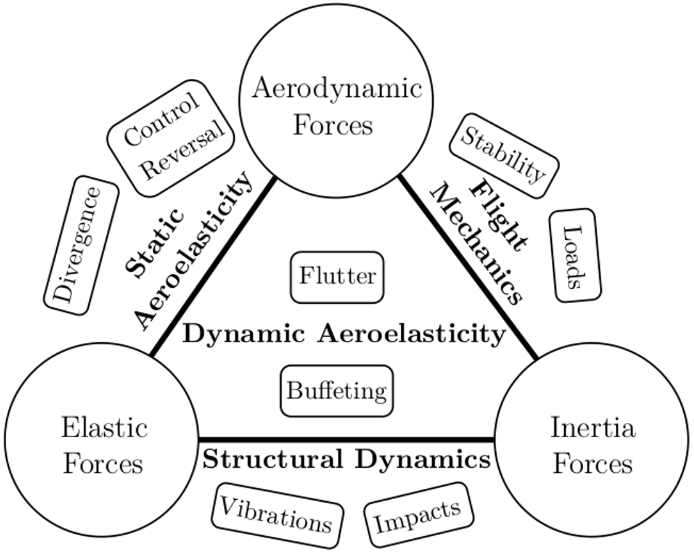
- Stochastic icing is being developed inside CHAMPS (See presentation from Hélène Papillon Laroche later today at 11:15am PDT)

- Previously developed in NSCODE with more programming challenges in C than in Chapel since growing mesh
    - Memory management
    - Parallelism
    - Additional types such as heap, list, etc.



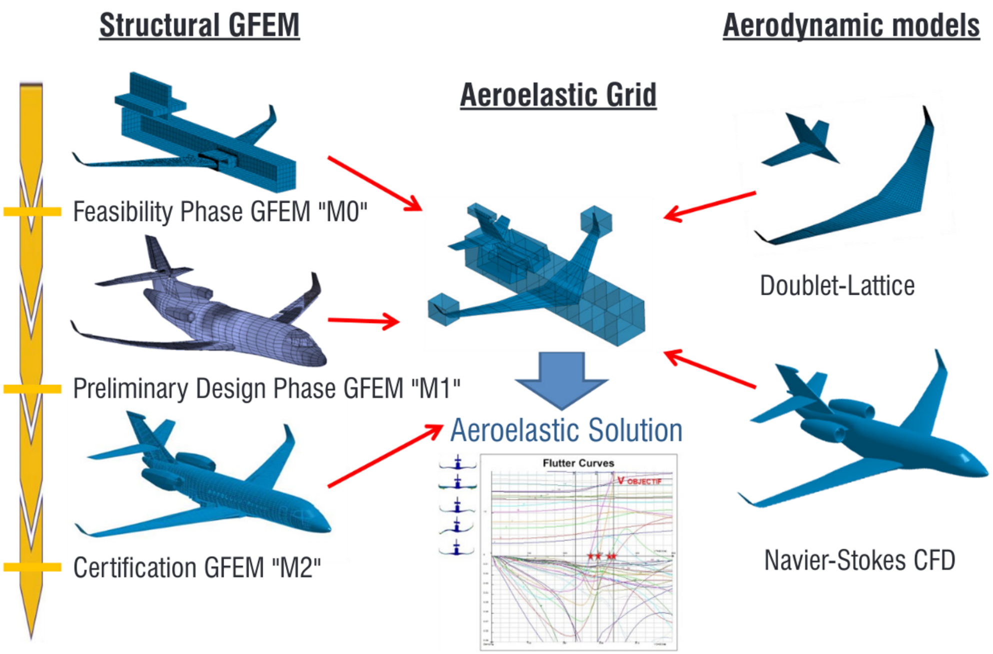
APPLICATIONS - AEROELASTIC SIMULATIONS

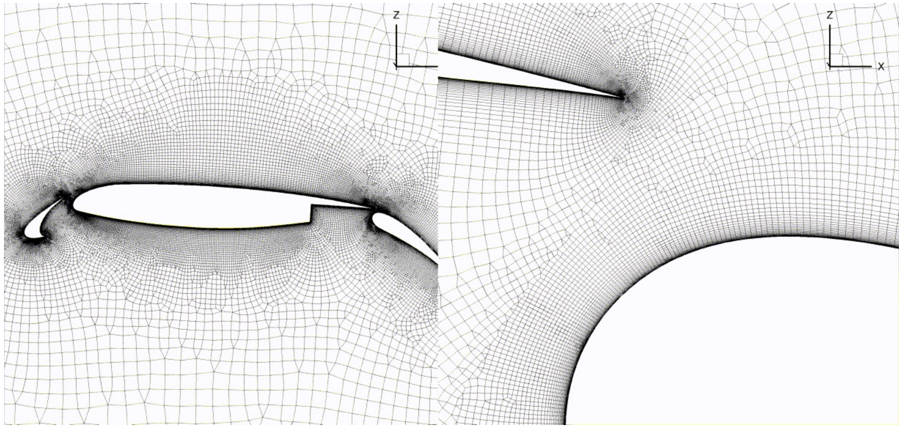
- Critical field for the design of commercial aircraft
- Requires the coupling of a Computational Structural Dynamic (CSD) model with a CFD model
- Flutter is a dangerous instability that can lead quickly to structural failure



APPLICATIONS - AEROELASTIC SIMULATIONS

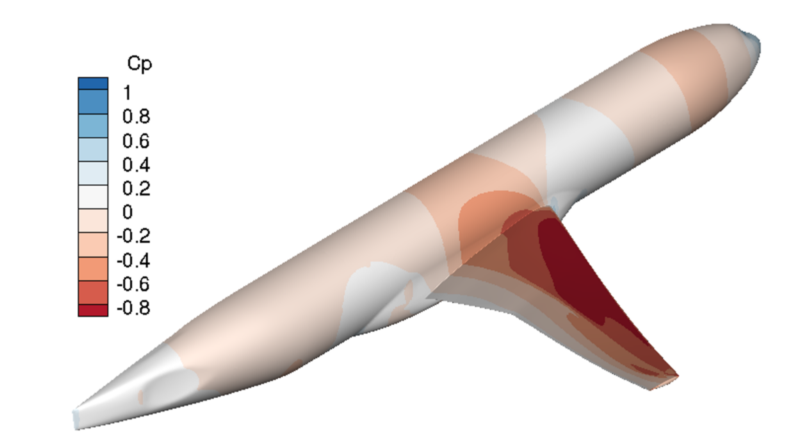
- High-fidelity aeroelastic simulations are complex
- The computational grids for the CSD and CFD model are not coincident
- Efficient algorithms are required to move the structure and the fluid mesh, while keeping the grid's quality

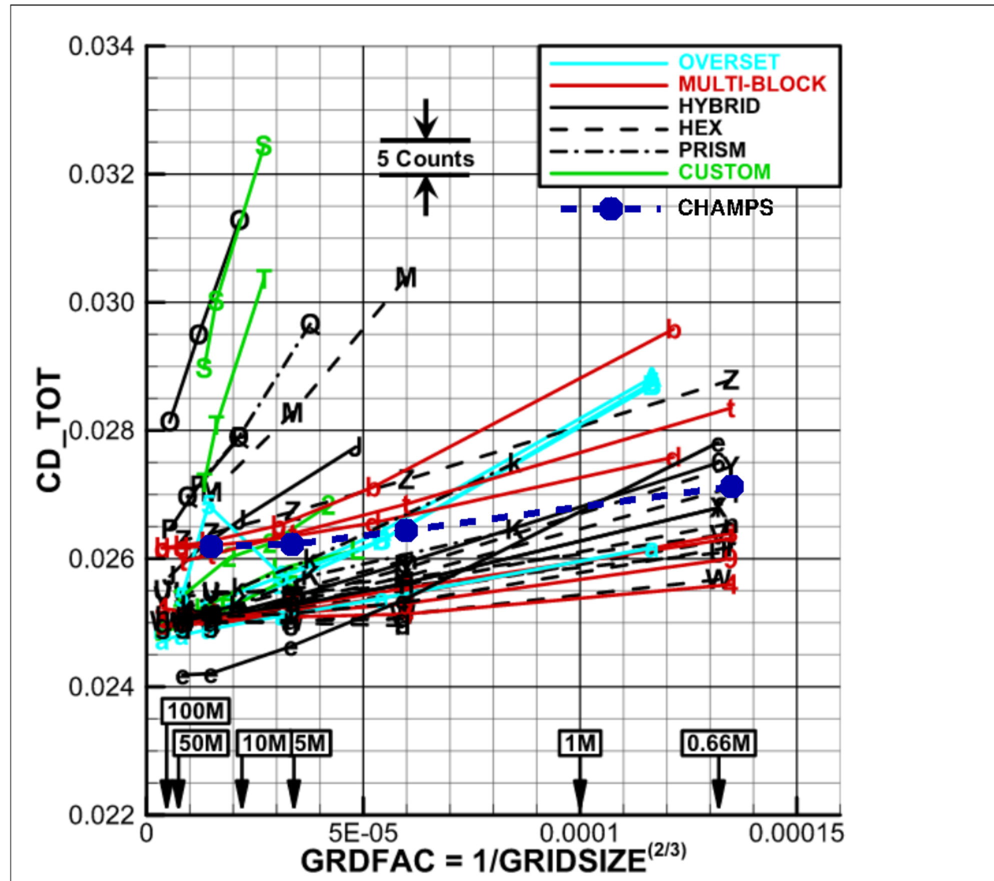




Ref: A Review of Industrial Aeroelasticity Practices at Dassault Aviation for Military Aircraft and Business Jets. doi: 0.12762/2018.AL14-09

The drag prediction workshop showcases the state of the art for the prediction of the aerodyamic performance of aircraft in cruise conditions, with participion from laboratories (NASA, ONERA, DLR, JAXA, etc.) industries (Boeing, Airbus, Embraer) and universities



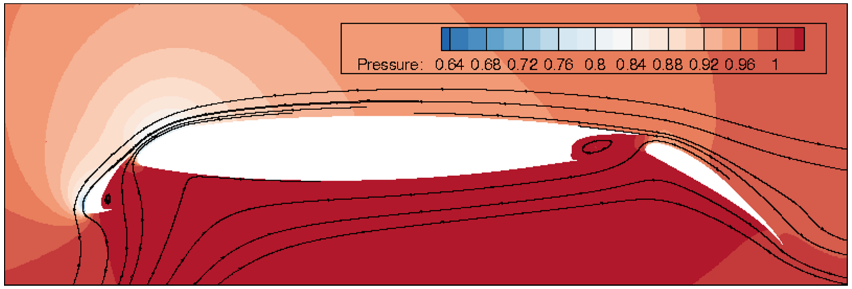


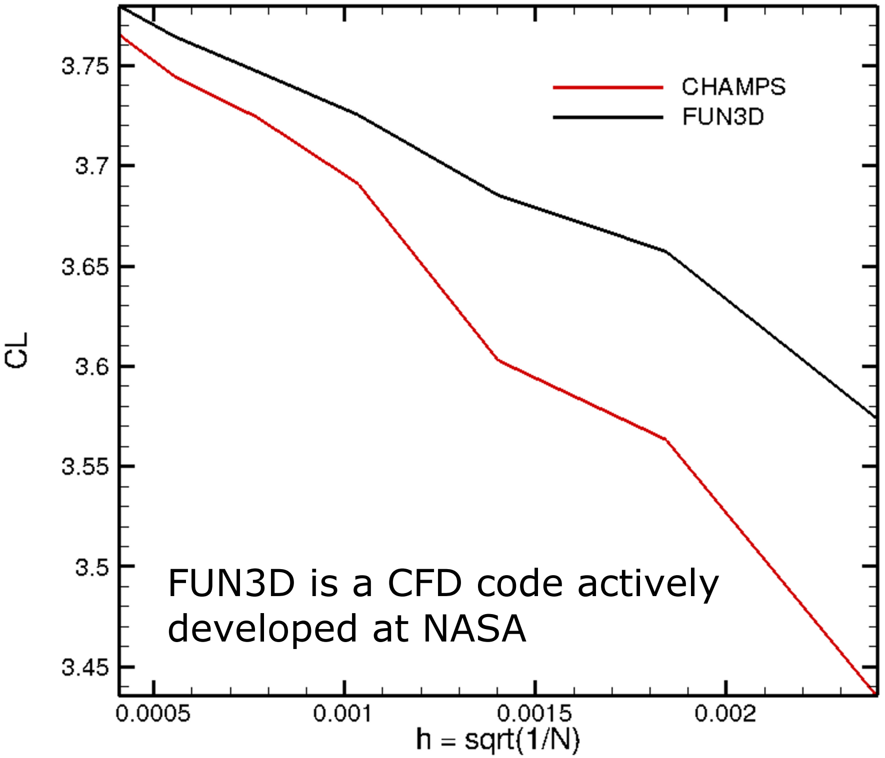
Ref: AIAA Drag Prediction Workshop 5 Summary presentation

APPLICATIONS - HIGH LIFT PREDICTION WORKSHOP 4

The high lift prediction workshop showcases the state of the art for the prediction of the aerodyamic performance of aircraft in take-off and landing configuration, with participion from laboratories (NASA, ONERA, DLR, JAXA, etc.) industries (Boeig, Airbus, Embraer) and universitites

Verification : 2D high-lift 3 elements ai

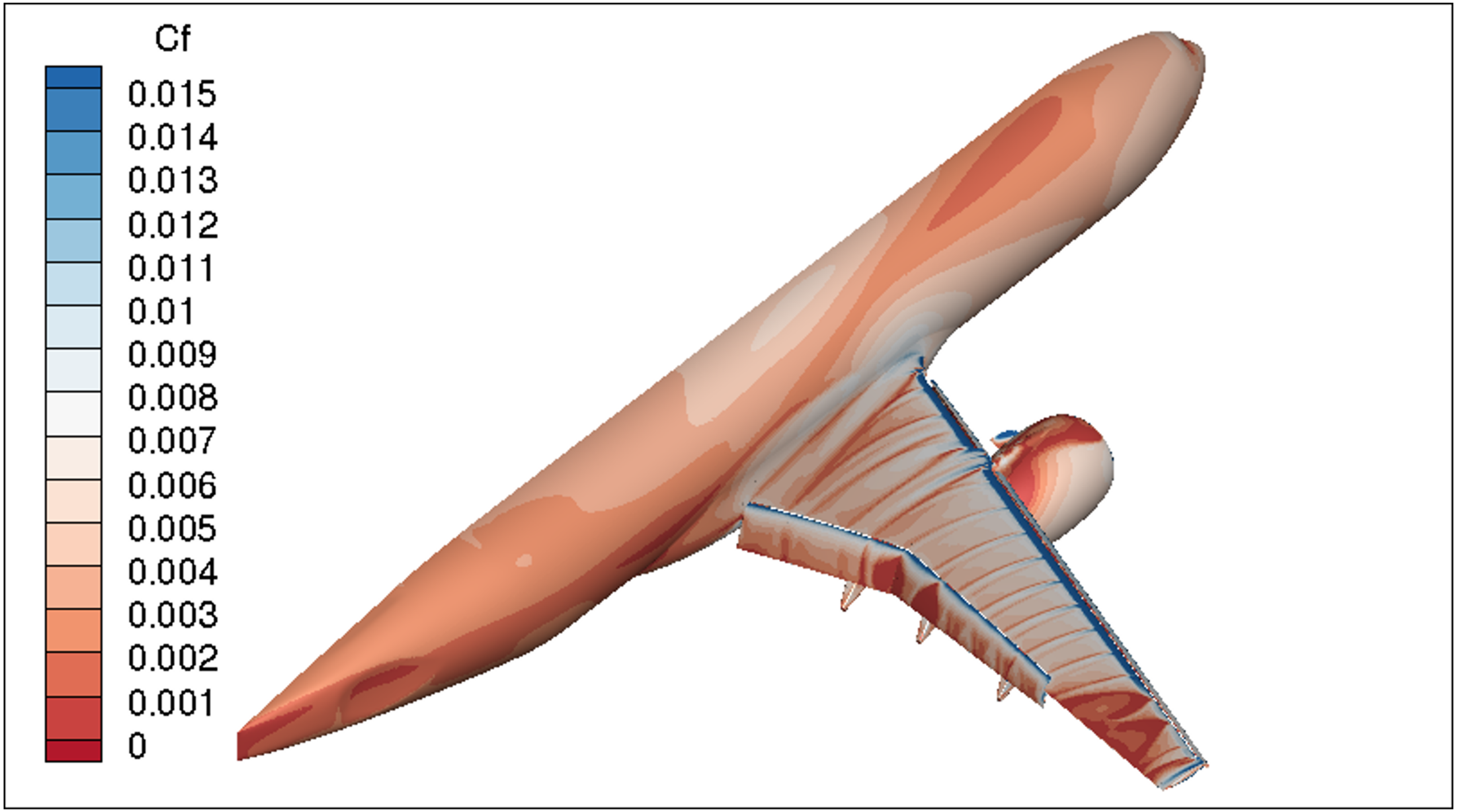




APPLICATIONS - HIGH LIFT PREDICTION WORKSHOP 4

Final goal : Predict the maximum lift coefficient of civil aircraft

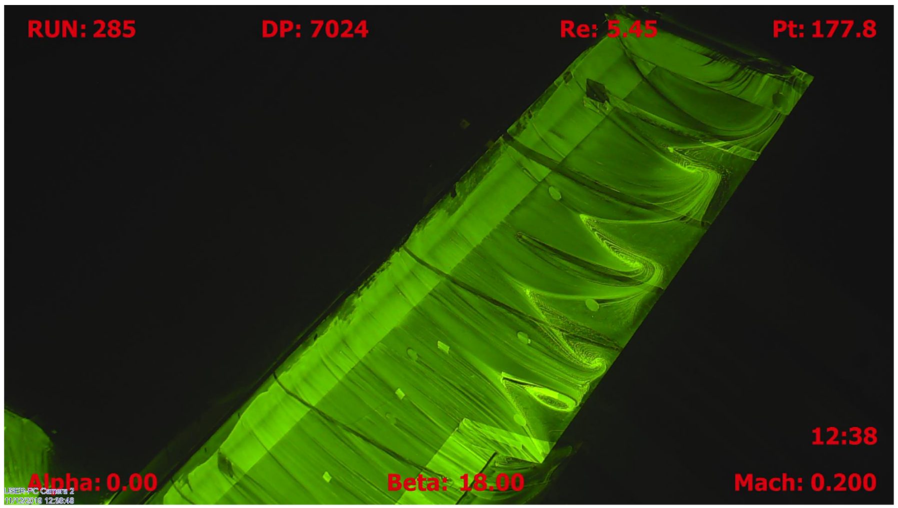
Mesh of 300 million cells (i.e. 1.8 billions unknowns)

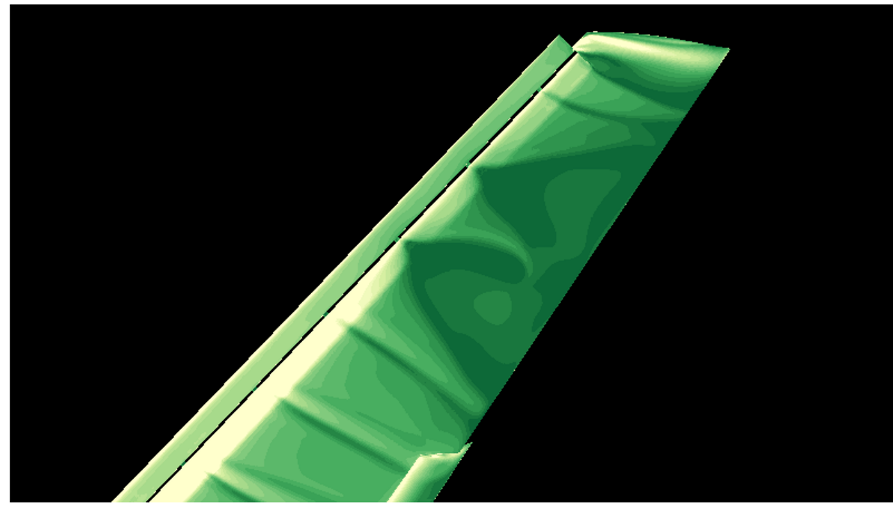


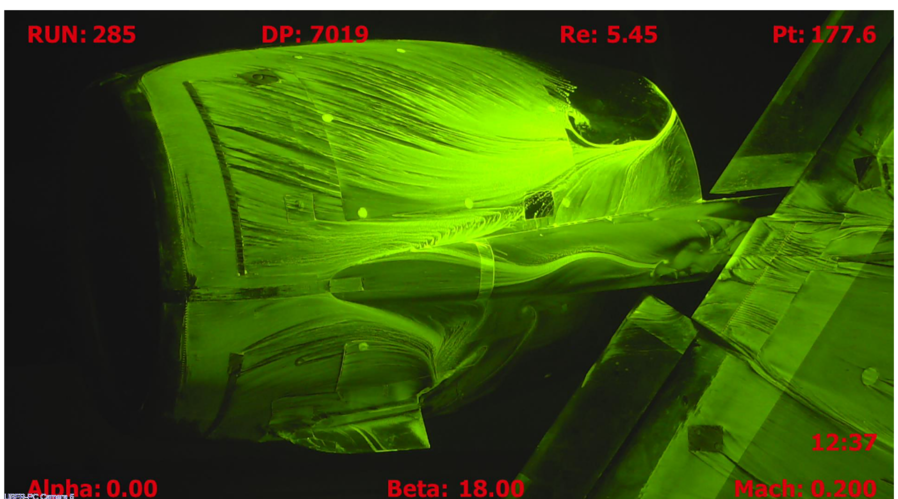
APPLICATIONS - HIGH LIFT PREDICTION WORKSHOP 4

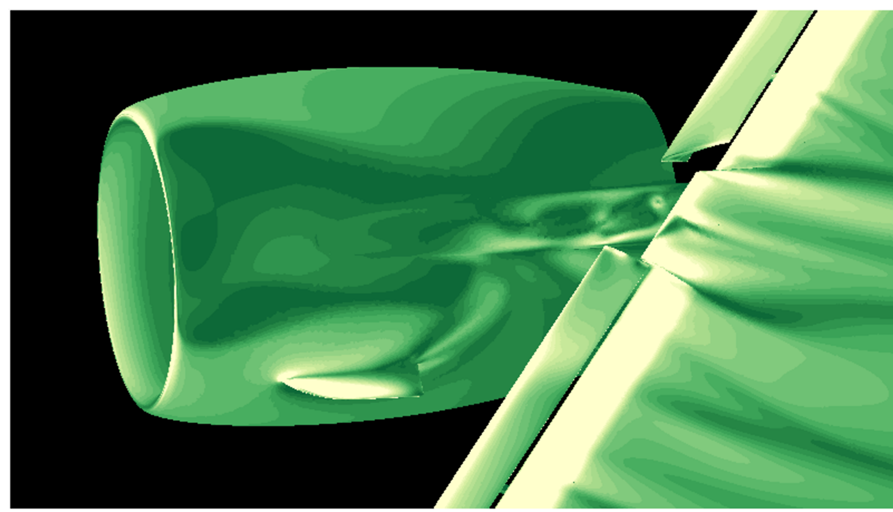
Experiments: AoA 17.98 deg

Champs: AoA 17.05 deg









SUMMARY: aircraft/aerodynamic design

- Aerodynamics is key within the aircraft design process
  - 3 phases: conceptual, preliminary, detailed

- Aerodynamic analysis relies on:
  - Physics, applied mathematics, HPC
  - A complex numerical workflow: parametrization, CAD, mesh, solver, post-processing

- Aerodynamic optimisation relies on:
  - Accuracy of the model
  - Computational resources (time, memory)

SUMMARY: modeling takeways

- The model accuracy is related, through the mathematical properties, to computing resources

- Several models are necessary to satisfy each design phase

	Phase	Accuracy	Computation time	Examined configurations
	conceptual	low	short	millions
$ $$$	preliminary	mid	mid	hundreds
$$	detailed	high	long	10-20

- The change in accuracy between each phase brings further costly iterative cycles

HPC

- HPC advances have had a tremendous effect on the aerospace industry (aerodynamics, structures, electromagnetics, flight simulation, etc.);
- Hardware: shared to distributed memory, CPU to GPU;
- Software: Strongly typed (FORTRAN) to abstract languages (C++), novel parallel paradigm (Chapel);
- Multidisciplinary knowledge is key for future advances, enacted through new multidisciplinary collaborative efforts (Modelers, Mathematicians, Computer Scientist, etc.);
- These challenges are all captured within NASA’s vision, embraced by the international community.

Questions?

- Special thanks to the organizing committee for this much appreciated invitation, and to HPE/Chapel team/developers for helping our research laboratory and our community.
- Safe, happy and planet-friendly flying!